Final Report

A 1000V, 120A Nondestructive Reserve Bias Second Breakdown Tester for Bipolar Power Transistors

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I. INTRODUCTION

This report summarizes the features concerning the design and fabrication of a nondestructive reverse bias second breakdown (RBSB) tester for high power bipolar transistor. The tester is rated at 1000V and 120A. The primary goal in developing the RBSOA tester is to be able to take a transistor under test (TUT) into breakdown and save it from destruction so that repeated measurements could be made. Nondestructive testing is essential for two reasons. One is that high power transistors are too expensive to perform destructive testing for RBSB characterization on a statistical basis. More importantly, a nondestructive tester permits one to investigate the device RBSB characteristics under various driving conditions, using the very same device. As we often observe that devices of the same kind may exhibit different RBSB characteristics.

The National Bureau of Standards has successfully built a RBSOA tester [1] and through which many useful insights and understanding of reverse-bias second breakdown characteristics of power transistors have been gained and reported in many recent literatures [2-5]. The current capability of the RBSOA tester built by NBS is, however, limited to only 30 Amperes. This limitation excludes the use of the tester for high current power transistors which has been recently made available by many major power device manufacturers in the world such as Westinghouse, GE, Motorola, Westcode, Fuji, Toshiba, Mitsubishi, Power Transistors, Powertech and Thompson CSF, etc. The tester built and tested at Virginia Polytechnic Institute and State University operates in the same principles as the NBS tester, but the current capability is approximately 4 times larger.

Summarized in the following are some expected benefits for the RBSOA tester.

1. Data obtained from second breakdown measurements can be used to establish reverse-bias safe operating areas (RBSOA) of a transistor from which guidelines for selecting snubber components and base-drive requirements can be established.

2. Construction of a tester will make it economically feasible to characterize the breakdown capability of high power transistors. It not only makes it possible to provide fundamental information for the device manufacturers to improve the device second breakdown ruggedness but also provides design guidelines for optimal snubbing and base drive.

3. Literatures on second breakdown have been limited to discrete device of low power rating. Little information on second breakdown is available for Darlington transistors even for low power devices. Initial tests by VPI SU and NBS jointly have discovered that the

second breakdown phenomena in power Darlington are not quite the same as its discrete counterpart [5]. Interesting and important characteristics have been observed for device with/without turn-off speed-up diode, for example (across the emitter and base terminals of the driver transistor). The second breakdown information obtained from the Darlingtons should benefit the circuit designer for knowing the limitation of the device and its configuration. The second breakdown characteristics of four-terminal power Darlingtons when two independent reverse base drives are applied simultaneously for a fast turn-off action can be investigated also by the tester.

4. It is recently reported that the second breakdown phenomenon can be also observed for GTO and power FET due to the existence of a bipolar transistor within its structure. The second breakdown tester can be employed to study the second breakdown characteristics of power FET.

II. PRINCIPLES OF OPERATION

Fig. 1 shows the basic circuit block of the tester. The TUT is connected in a common emitter configuration with an inductive load in the collector circuit. When the TUT is switched on with the forward bias pulse, collector current rises. When the TUT is driven with the turn-off pulse, the collector voltage reaches a high value before there is much reduction in the collector current. A variable voltage clamp acts to prevent the collector voltage from going above the preset voltage level. Once the collector voltage reaches the clamp voltage, the inductor current is diverted from the TUT to the clamp supply. The clamp voltage is normally set below device BV_{CBO} to prevent the device from being destroyed. The second breakdown is characterized by a rapid fall in voltage before the collector current reaches zero. Typically the collector voltage of the TUT may fall about 500 V in 10 to 20 ns. This rapid fall is detected in the tester with a capacitive pickup that triggers the high speed shunt circuit. This circuit removes the remainder of the energy stored in the inductor load. This circuit shunts the clamp voltage to a negative power supply. The clamp supply for the TUT has an additional diode-resistor-inductor network that allows the clamp voltage to go negative for a short period of time and then decay to zero. This is done to overcome the inductance in the wire that connects the protection circuit to the TUT. Several power Schottky diodes are put in series with the collector of the TUT to effectively open the collector lead when the clamp voltage is driven negative. When the protection circuit fires, the clamp supply and the V_{CC} supply are turned off. The protection circuit

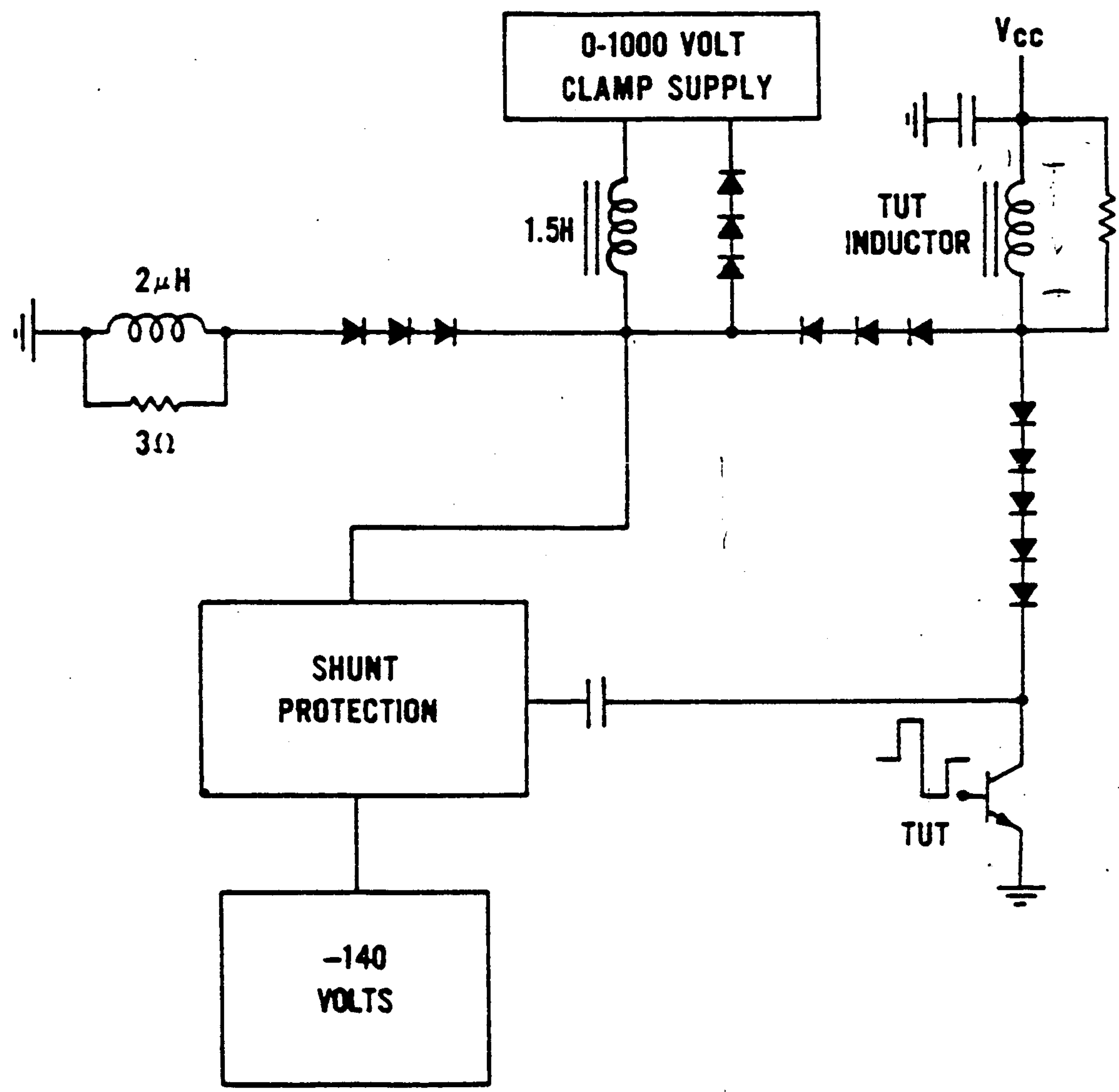

Figure 1. Key components surrounding the TUT.

Courtesy of National Bureau of Standard
Publication 400-54 "A Reserve Bias
Safe Operating Area Transistor Tester" 1979.

should remove the current from the TUT as quickly as possible and handle over 1000 V and 120 A simultaneously.

III. DESIGN AND FABRICATION OF THE RBSB TESTER

As mentioned above, NBS basic design approach is adopted in the present tester. The detail of the NBS tester can be found in Ref. [1]. However, significant effort is required to modify both the electrical design and the mechanical layout to bring up the current capability to 120 Amps. The tester consists of three basic components: collector supply, base drive and shunt circuit. The collector supply is a stand-alone, variable 300V, 100A commercial unit featuring remote enable required for this application. The base drive design is similar to NBS tester with the modification of higher base drive output current and the option of two reverse base drives for Darlington Transistors. The basic shunt design, however, is supplemented to increase the speed and power handling capability along with the appropriate power supply and layout modifications. This modification, explained below, provides the test system capacity required to reliably test high power devices at current levels up to 120A and 1000V.

3.1 Base Drive Circuit and Control

The base drive chassis contain the control circuits for the tester including timing, logic, pulse generators and amplifiers, base current measurement amplifier, low voltage power supplies and the gated high voltage clamp supply. Base drive circuit provides three independently adjustable current sources, one for forward base current one for reverse base current and the third one for the reverse base current of the second base terminal of some Darlington transistor. The forward base current level is adjustable from 1A to 30A and the reverse base current is adjustable from 2A to 30A. For both reverse drive circuit, a voltage clamp of adjustable magnitude (0 to 15V) is provided. The clamp is used to limit the reverse voltage across transistor base-emitter junction.

Fig. 2 shows the front panel of the actual tester hardware. DUT is located in the middle left of the photo. The box in the middle of the photo is a inductor used as the load of the testing circuit. The series of small knobs in the front of the panel are for adjusting the base drive conditions for the DUT. Starting from the left, the first two knobs are forward base current width control; the next two are forward base current amplitude control. The fifth and the sixth knobs are reverse base current width control. The seventh knob is for setting the base-emitter clamping voltage. The

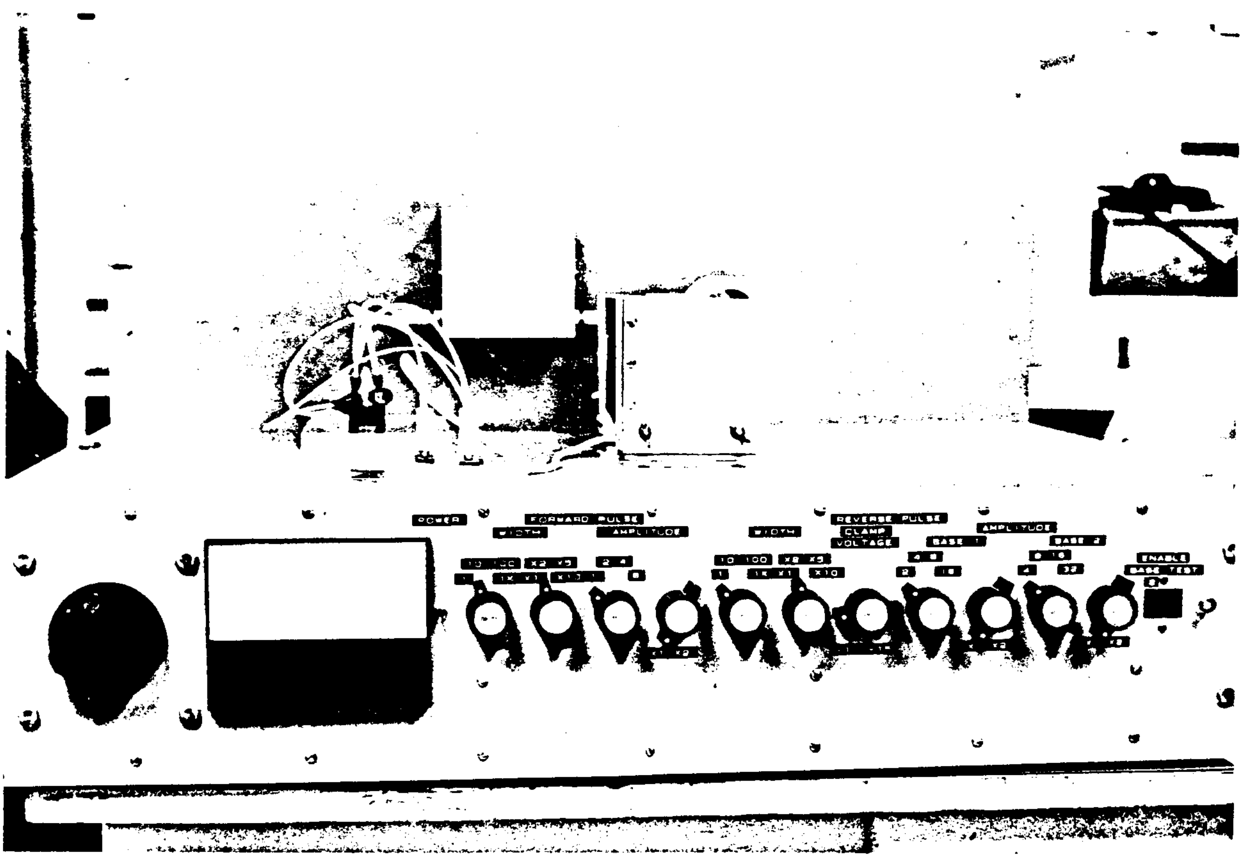

Fig. 2. Tester Front Panel

ninth and the tenth knobs are for reverse base current amplitude control for base drive #1 and the last two are for base drive #2.

Special attention was paid to the layout of the base drive circuit to reduce the lead length and inductances of the base circuit loop. A special audio speaker cable was used to carry the base-drive signal for the pulse amplifier chassis to a pair of binding posts mounted on top of the tester where the TUT is located.

3.2 Current Shunt Design

The circuit design and the mechanical layout of the Shunt Circuit are crucial to a successful attempt to raise the tester capability to 1000V, 120A level. A detailed description of the circuit is given below. The shunt circuit is basically a 125 kw peak power amplifier. The output stage consists of a tri-concentric circular array of sixty-four 6LF6 power vacuum tubes wired in parallel as shown in Fig. 3. The actual hardware is shown in Fig. 4. The entire amplifier is assembled on nine printed circuit boards and mounted on a ground plate. A 3-inch octagonal input board has, extending out from each side, eight identical trapezoidal output boards forming an outer 21-inch octagon. The tube array of 18, 14 and 10-inch diameters

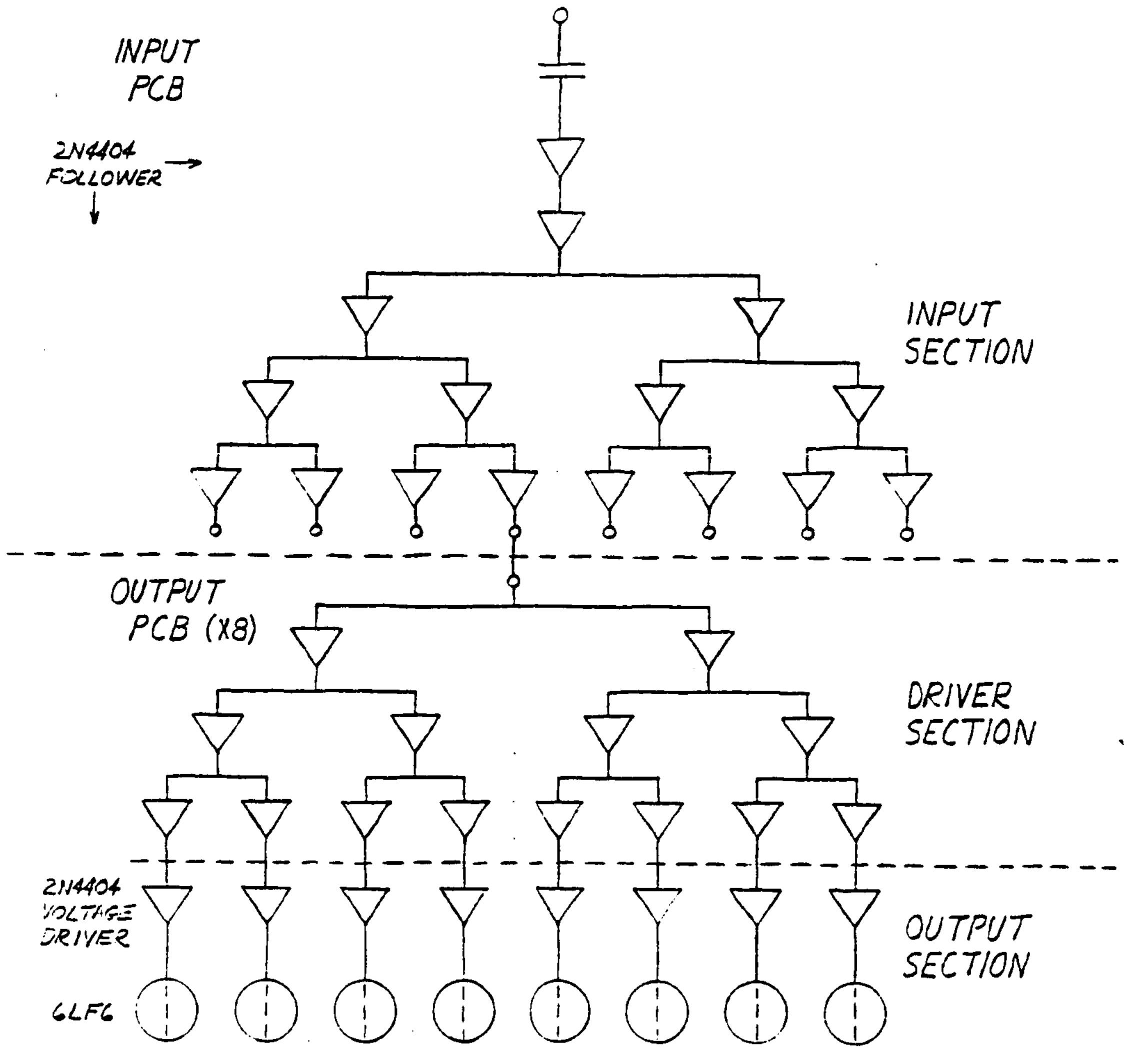

Fig. 3. Amplifier stages of the sixty-four GLFG vacuum tubes.

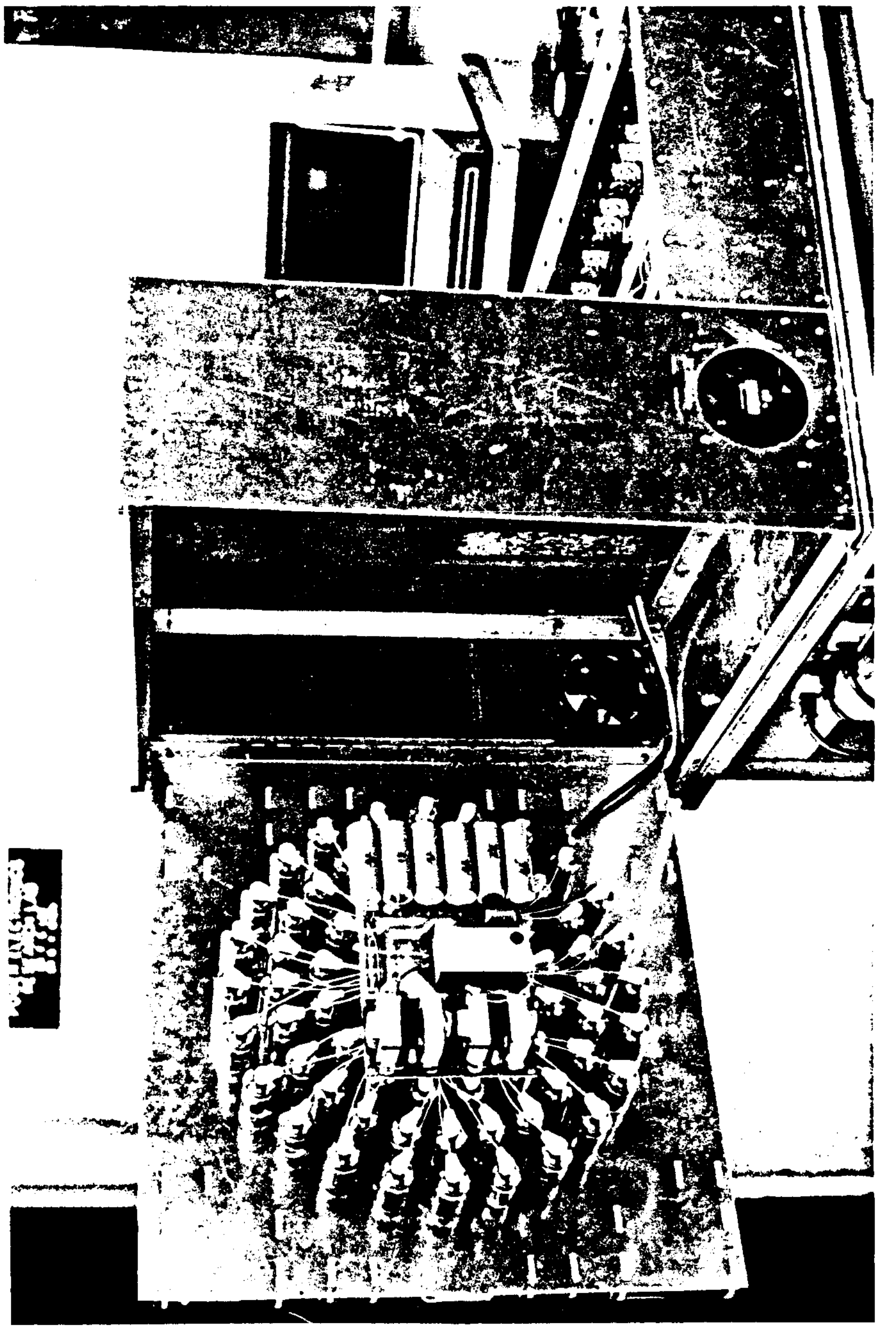

Fig. 4. Vacuum Tube Arrays for the Shunt Circuit

is centered on the octagon with eight tubes per output board.

Fig. 5 shows the lay-out diagram of the input board, the output board and the tube array. The input board is used to detect the DUT second breakdown signal. The output boards are cascaded current amplifiers used to turn on the tube array at the other side of the output board. Fig. 6 shows the hardware of both the input and the output boards. Fig. 7 shows the blow-up view of the input board. A BNC jack, mounted in the center of the input board, provides the input gate signal via coaxial cable from the DUT collector. A small wire loop extending from the BNC jack is placed 1/4" from a pick-up wire at the base of the input transistor, coupling the DUT collector to the shunt input. The minute capacitance enables the input to gate only on the rapid fall of the collector voltage that characterizes device breakdown while ignoring the slower fall of normal turn-off.

The gate signal then branches and radiates out through cascaded current amplifiers to sixty-four parallel tube output stages. The tube plates are tied together above the center of the array via a lead and plate clip from the top of each tube. This common is then connected to the DUT and the inductor through a network of blocking diodes. When turned on, the tubes

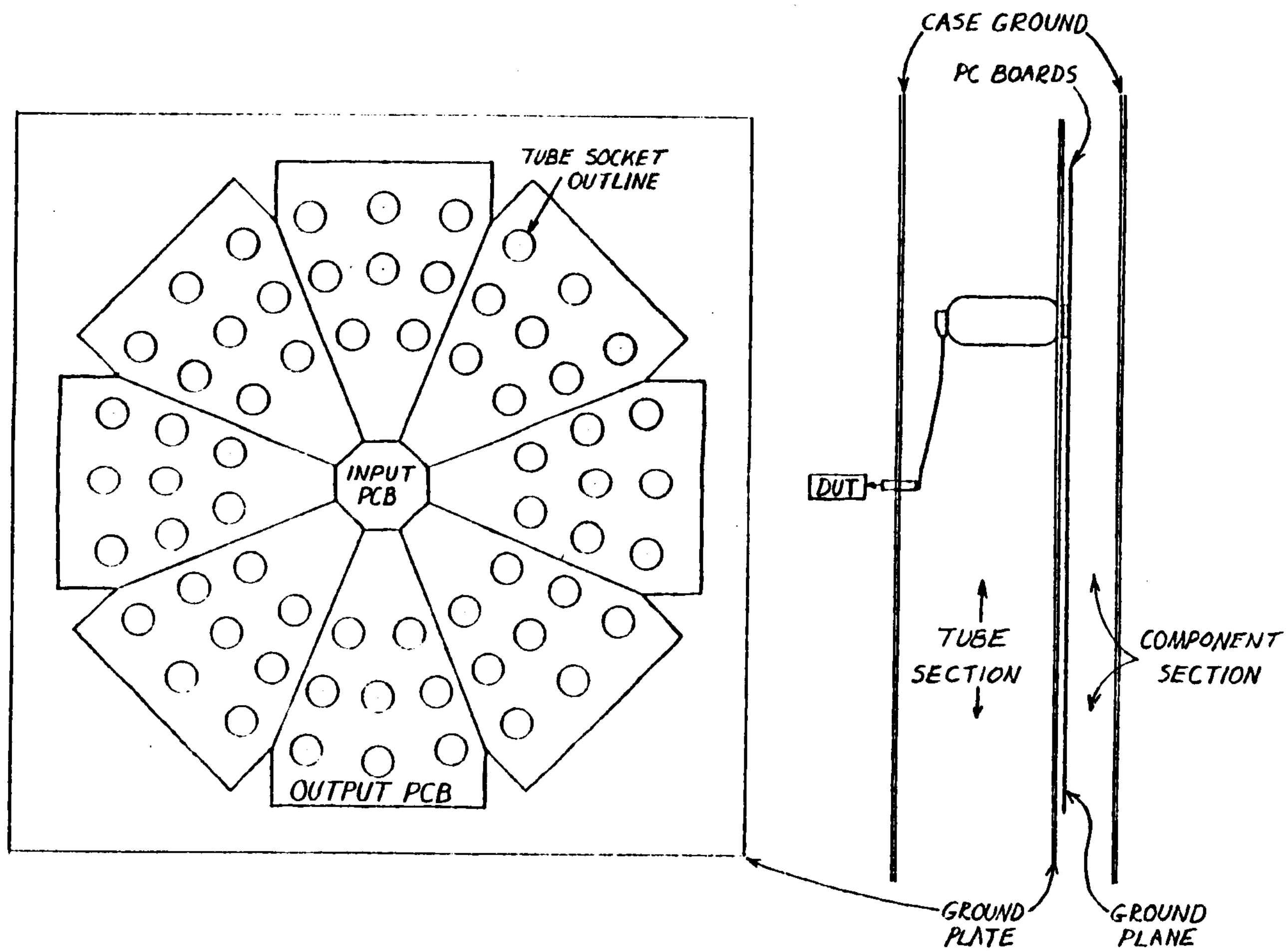

Fig. 5. Lay-out diagram of the sixty-four parallel tube output stages for current shunt.

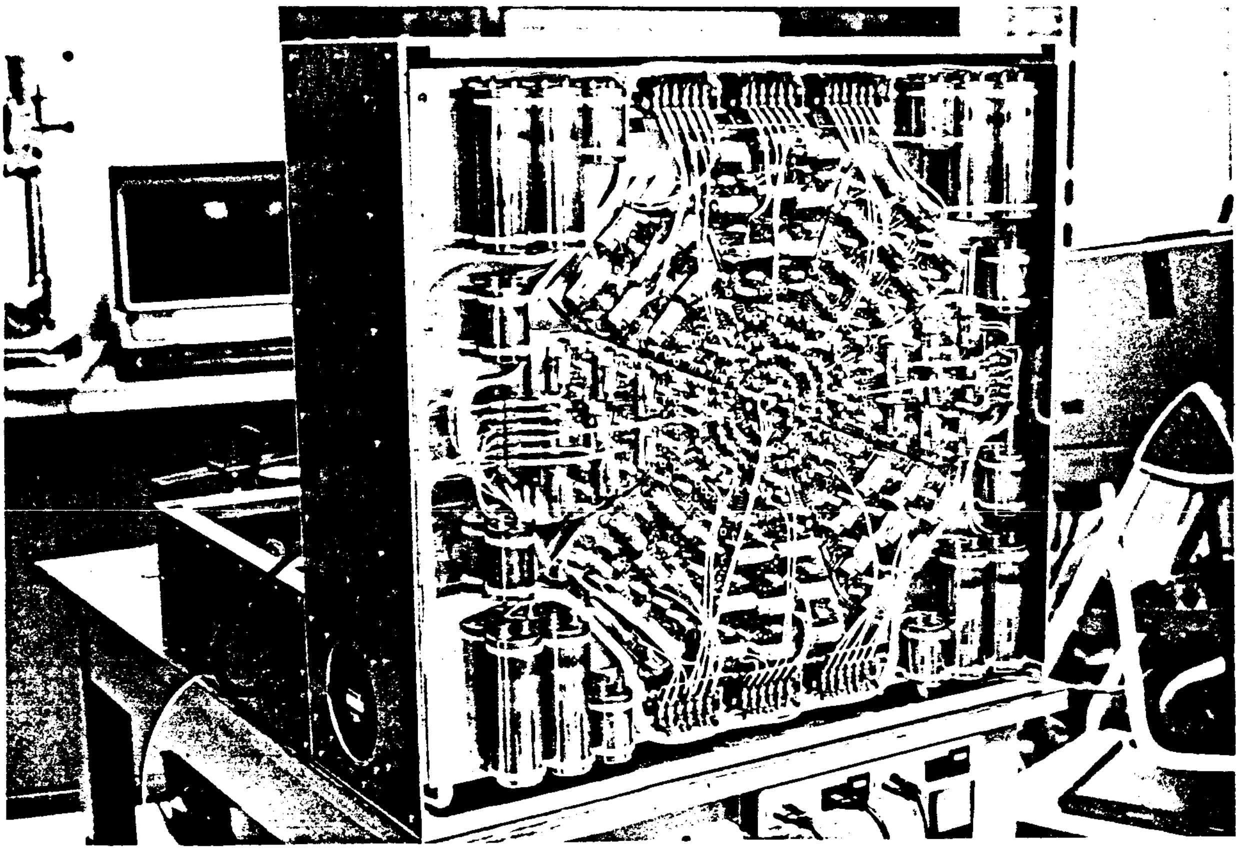

Fig. 6. Part of Shunt Circuit - (a) Detection Circuit (Middle Octave Board), (b) Current Amplifier Circuit (the surrounding 8 boards). The other part of the Shunt Circuit is Vacuum Tubes Arrays located at the rear side of the boards.

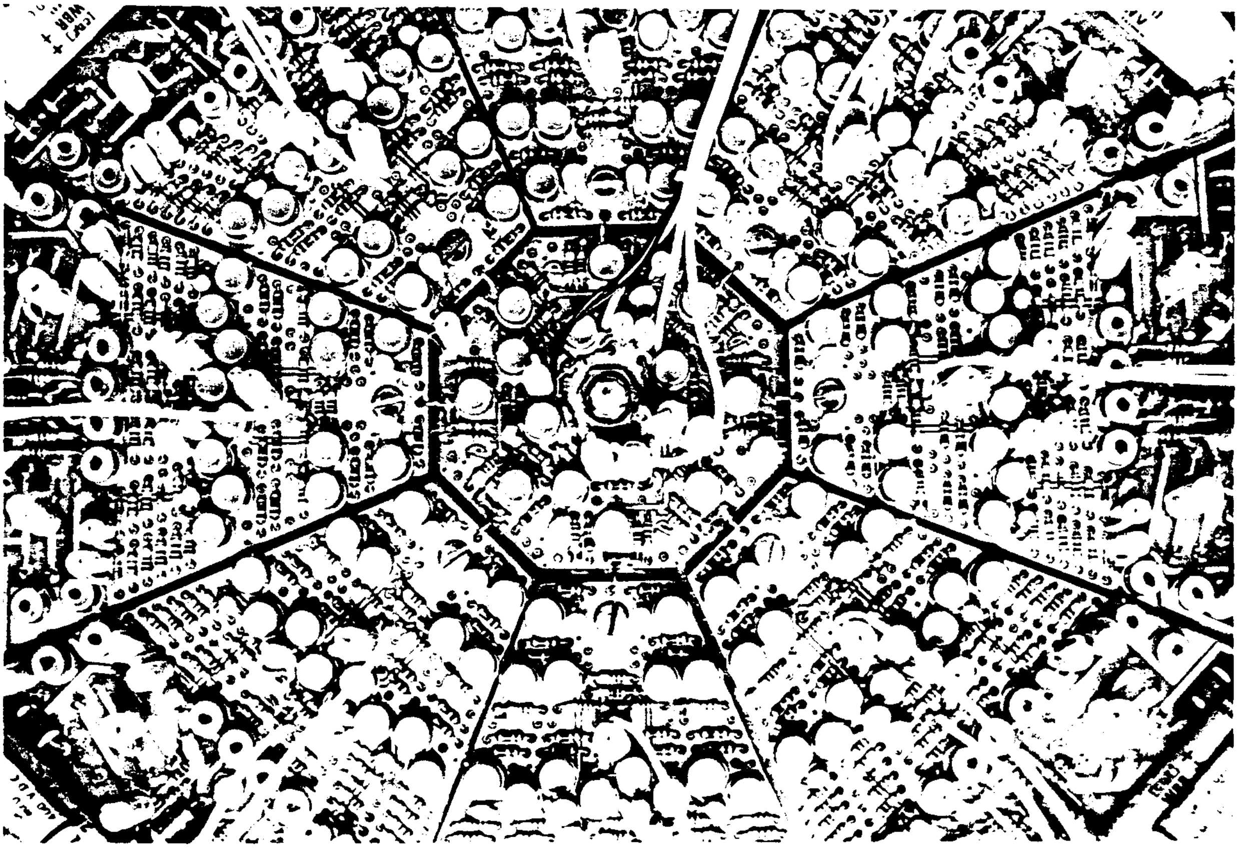

Fig. 7. Close View of Shunt Detection Circuit Board

provide a low impedance path between the DUT inductor and a common -150V supply on the cathodes. The remaining inductor energy is dumped, the collector supply is disables and, after a delay, the system is reset automatically in preparation for the next test.

To minimize signal delay and interference, all devices are biased in the active region and the entire amplifier layout is fully symmetrical about the center input jack. All of the solid-state amplifiers are mounted within the smallest diameter of tubes on the PC boards with subdivided ground planes and high speed layout. Each ground plane is tied to the common ground plate through PC Board mounting hardware.

3.3 Tester Circuit Diagrams

Because of the complexity involved, the tester circuit is drawn in nine separate figures shown in the Appendix. The figures are grouped according to the circuit functions. Each diagram is shown in detail and needs no further explanation. For an overview of the tester block diagram, readers should refer to Fig. 1.

IV. EVALUATION OF THE TESTER

This section summarizes the results of the evaluation of the tester. Five device types were tested to demonstrate the feasibility of nondestructive testing and to explore the upper limit of the tester.

4.1 Operation of the Tester

The tester can be operated in two different modes, repetitive measurement mode and one-shot measurement mode. In the repetitive mode, a signal generator is used to trigger the tester. Repetitive mode is normally used for the adjustment of the circuit condition to obtain certain measured waveform for one sho measurement. In the one-shot measurement, a manual trigger button is used. The test will execute 5 second after the manual trigger button is released. A high speed storage scope is used to capture the one shot measurement waveform. The results of test examples are given in the following section.

4.2 Demonstration of Nondestructive Testing of Transistor Reverse Bias Second Breakdown

Five different transistor type were tested.

G.E.	D67DE6
Fuji	ET133 ET102 ET127
Westinghouse	KD324510-06-Q1

Figs. 8 to 22 show the oscillograms of the test results for several different devices under various circuit conditions. Take Fig. 8 for illustration. A family of three V_{CE} waveform is recorded in this figure. Each waveform corresponds to a different forward base current. As can be seen from the figure, V_{CE} waveforms starts at nearly zero voltage (at the origin) when the base drive turn-off signal is given. Then the voltage rises to the peak at that point second breakdown occurs and V_{CE} drops sharply which triggers the shunt circuit which diverts the collector current from the device and saves the device from permanent damage. From the figure, it can be seen that the breakdown voltage is 420V when forward base current I_{BF} is 1A, 430V when I_{BF} is 2A and is 460V when I_{BF} is 5A. All the three tests were conducted at collector current of 30A. For the rest of the oscillograms shown, the interpretation of the waveforms is similar and will not be repeated here. Rather, general observations of the testing results will be summarized below.

4.3 Remarks about the Test Results

- All the devices tested under 60 A of collector current has survived the second breakdown without noticeable degradation. Leakage current I_{CBO} were measured before and after the second breakdown to check if any degradation occurs. In other words,

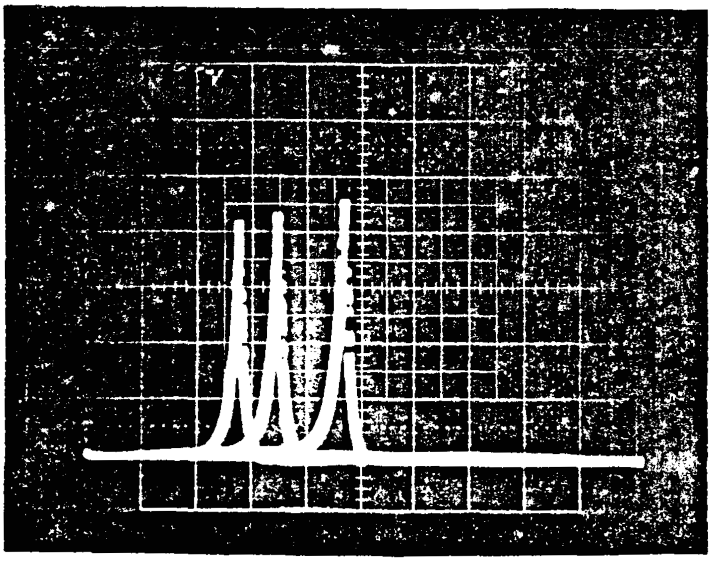

Fig. 8. V_{CE} Waveforms of the Fuji ET-133-02 Device at I_C = 30 A; V_{CCL} = 600 V, I_{BR} = 10 A and I_{BF} = 1,2,5 A (Scale: 1 μs/div, 100 V/div)

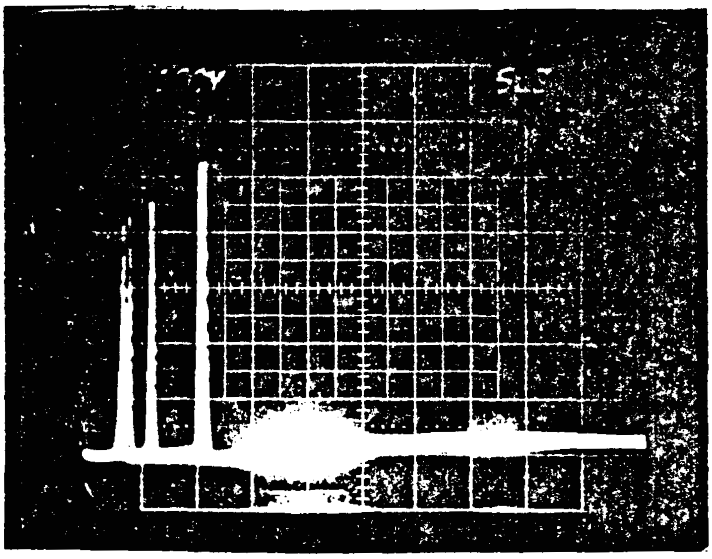

Fig. 9. V_{CE} Waveforms of the Fuji ET-133-02 Device at I_C = 30 A, V_{CCL} = 600 V, I_{BF} = 2 A and I_{BR} = 15,10,5,2A (Scale: 5 μs/div, 100 V/div)

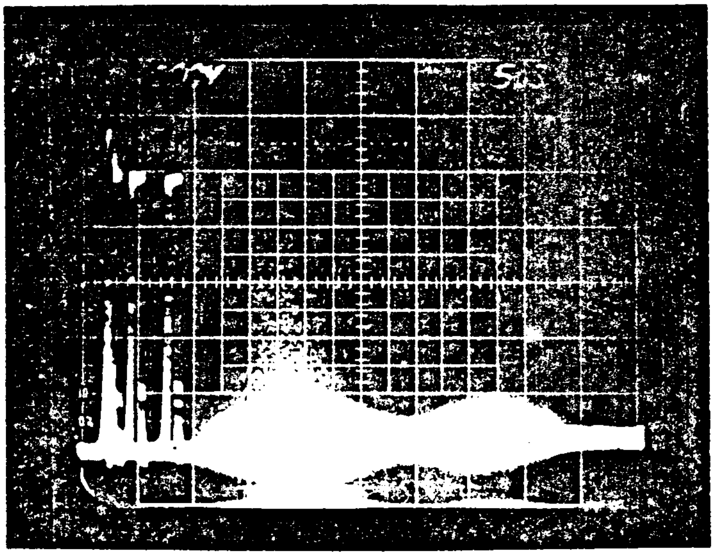

Fig. 10. V_{CE} Waveforms of the GE DG7DE6-03 Device at I_C = 30 A, V_{CCL} = 600 V, I_{BF} = 2 A and I_{BR} = 15,10,5,2 A (Scale: 5 μs/div, 100 V/div)

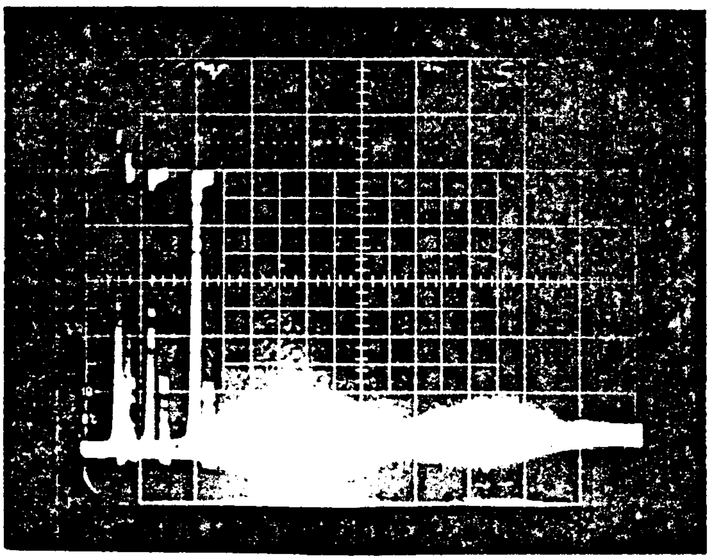

Fig. 11. V_{CE} Waveforms of the GE DG7DE6-03 Device at I_C = 30 A, V_{CCL} = 600 V, I_{BF} = 6 A, and I_{BR} = 15,10,5,2 A (Scale: 5 μs/div, 100 V/div)

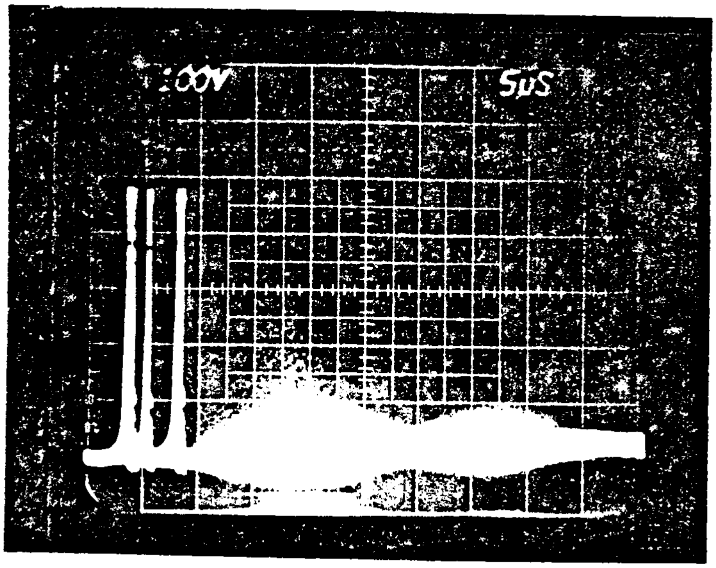

Fig. 12. V_{CE} Waveforms of the GE DG7DE6-03 Device at I_C = 60 A, V_{CCL} = 600 V, I_{BF} = 2 A, and I_{BR} = 15,10,5,2 A (Scale: 5 μs/div, 100 V/div)

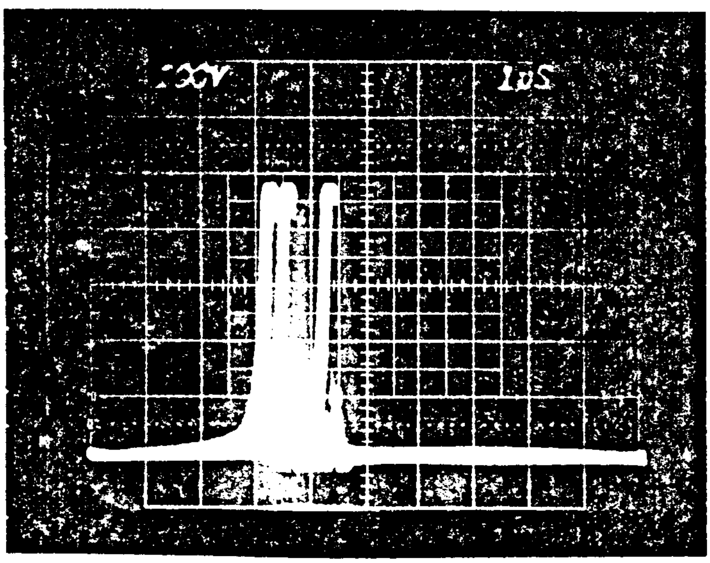

Fig. 13. V_{CE} Waveforms of the GE D67DEG-03 Device at I_C = 60 A, V_{CCL} = 600 V, I_{BR} = 10 A and I_{BF} = 1,2,5 A (Scale: 1 μs/div, 100 V/div)

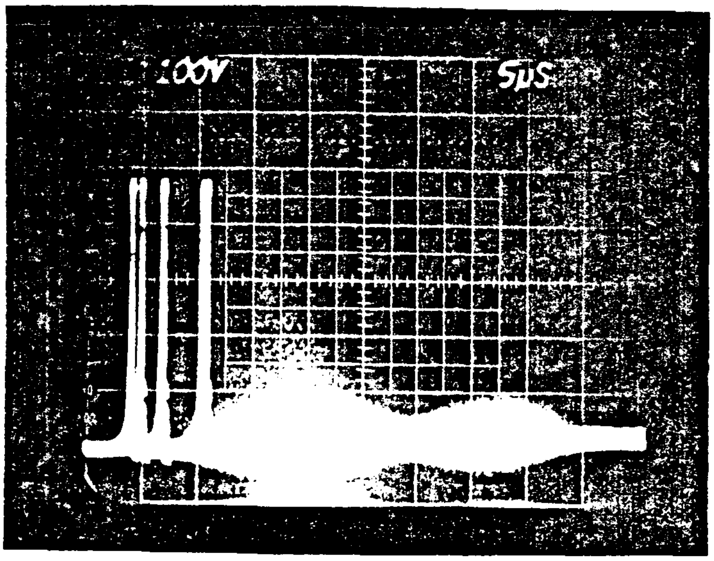

Fig. 14. V_{CE} Waveforms of the GE D67DEG-03 Device at I_C = 60 A, V_{CCL} = 600 V, I_{BF} = 6 A and I_{BR} = 15,10,5,2 A (Scale: 5 μs/div, 100 V/div)

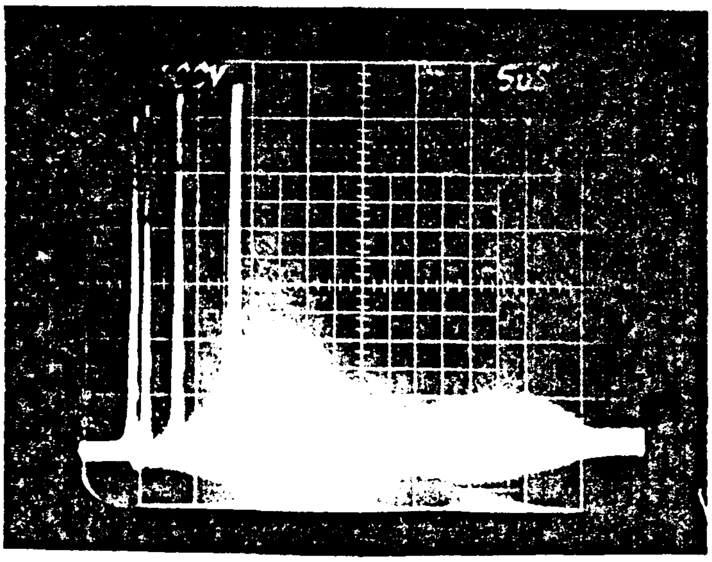

Fig. 15. V_{CE} Waveforms of the Fuji ET-133-02 Device at I_C = 60 A, V_{CCL} = 200 V, I_{BF} = 6 A and I_{BR} = 15,10,5,2 A (Scale: 5 μs/div, 100 V/div)

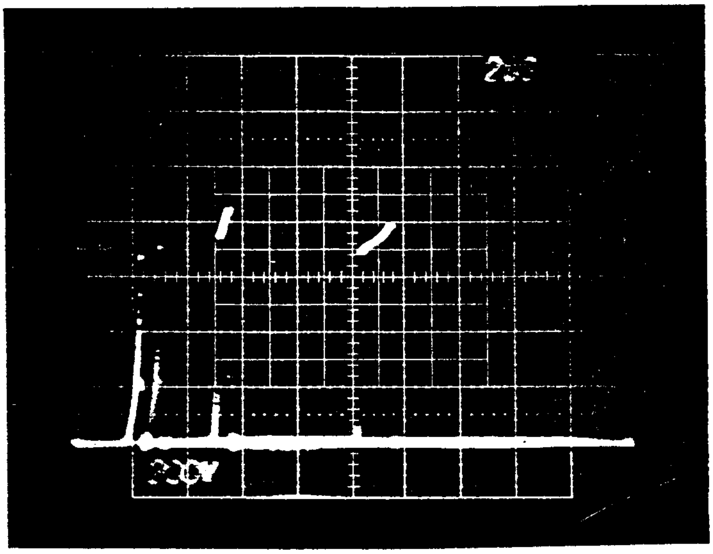

Fig. 16. V_{CE} Waveform of the Westinghouse KD324510-06-Q1 Device at I_C = 30 A, V_{CCL} = 900 V, I_{BF} = 2A and I_{BR} = 15,10,5,2 A. I_{CBO} = 1.4 μA at 400 V_{CB} before testing.
(Scale: 2 μs/div, 200 V/div)

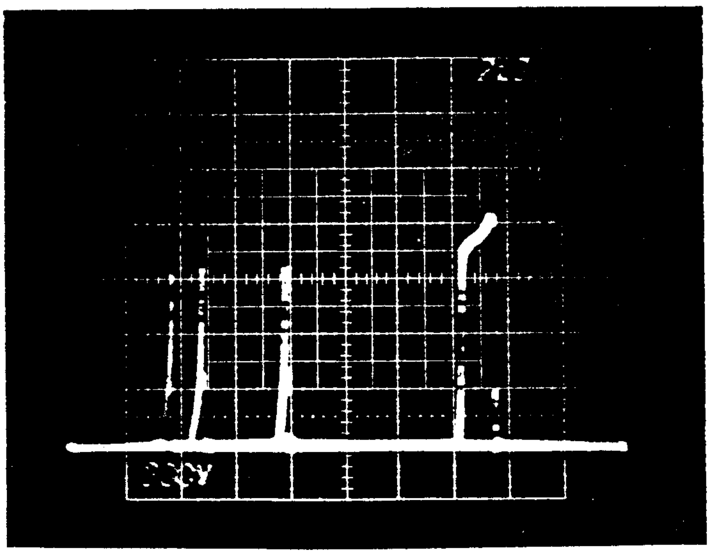

Fig. 17. V_{CE} Waveform of the Westinghouse KD324510-06-Q1 Device at I_C = 30 A, V_{CCL} = 900 V, I_{BF} = 6 A and I_{BR} = 15,10,5,2 A.
(Scale: 2 μs/div, 200 V/div)

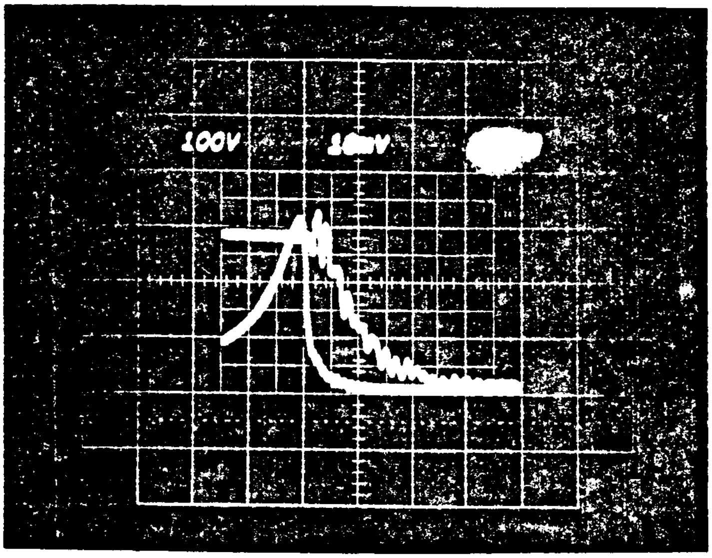

Fig. 18. I_C and V_{CE} Waveforms of the Fuji
ET-102 Device at I_C = 115 A,
V_{CCL} = 200 V
(Scale: 100 ns/div, 100 V/div, 20 A/div)

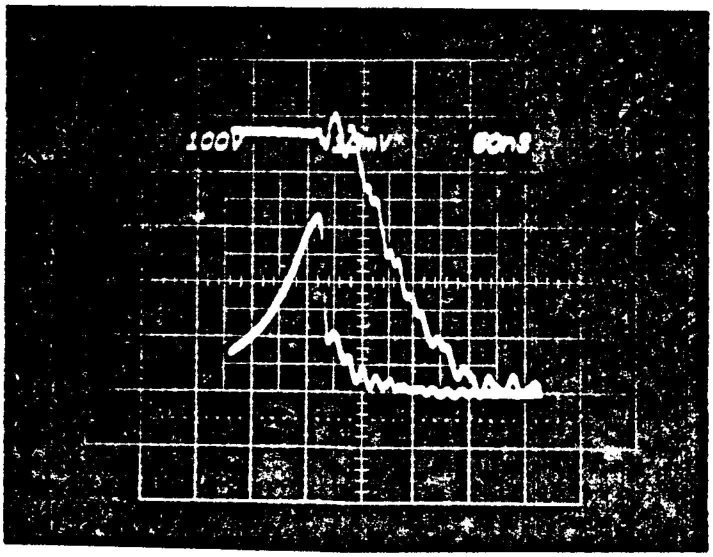

Fig. 19. I_C and V_{CE} Waveforms of the Fuji
ET-127 Device at I_C = 95 A
(Scale: 50 μs/div, 100 V/div, 10 A/div)

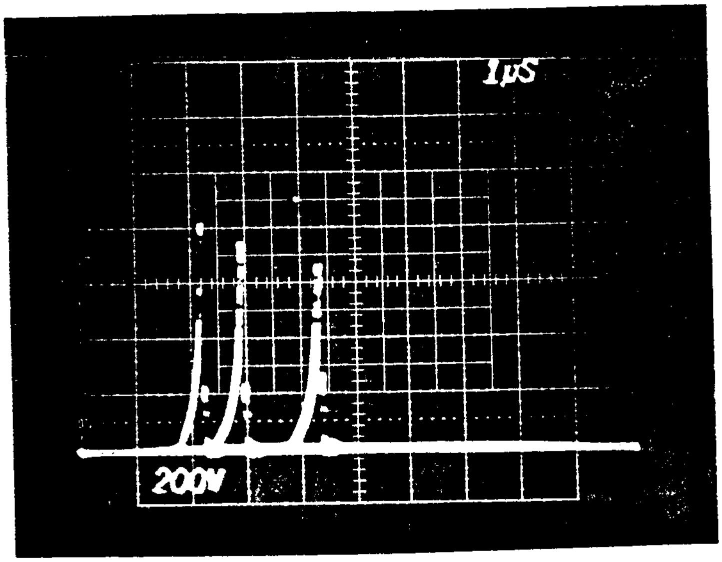

Fig. 20. V_{CE} Waveform of the Westinghouse KD324510-06-Q1 Device at I_C = 30 A, V_{CCL} = 900 V, I_{BR} = 10 A and I_{BF} = 1,2,5 A. I_{CBO} = 1.7 μA at 400 V_{CB} after 12 30 A tests.

(Scale: 1 μs/div, 200 V/div)

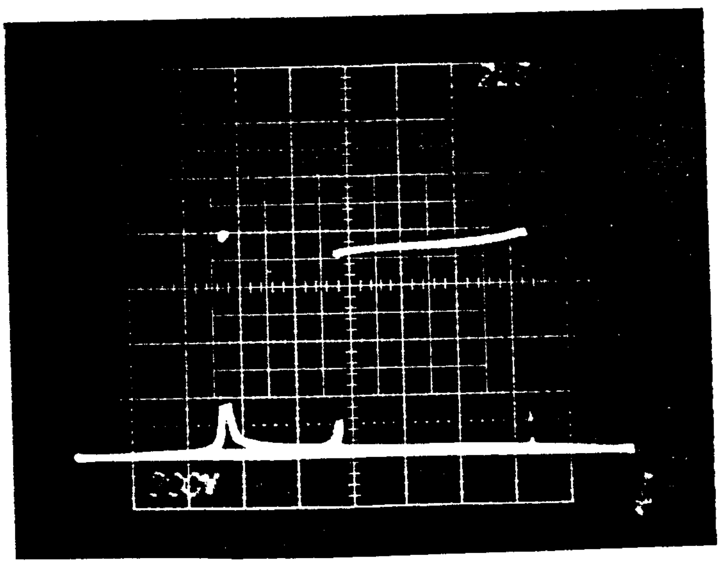

Fig. 21. V_{CE} Waveform of the Westinghouse KD324510-06-Q1 Device at I_C = 60 A, V_{CCL} = 900 V, I_{BF} = 2A and I_{BR} = 4, **2 A**

(Fatal)

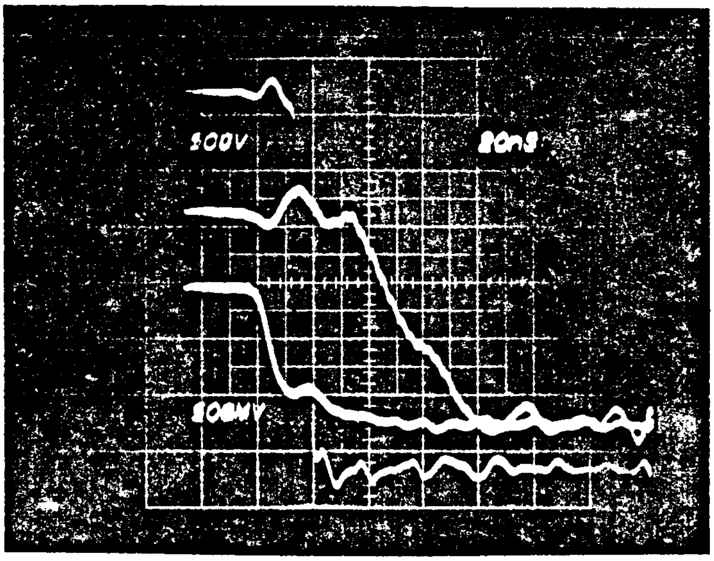

Fig. 22. Shunt Turn-on Time Measurement.

V_{PLATE}, V_{CE} and I_C are shown for GE D67DE6-03 Device.

(Scale: 20 μs/div, 100V/div, 5 A/div) completely nondestructive testing is successful for collector current under 60A.

- For high current tests (>60A), however, the device may or may not survive the test, depending on the device types. For example, Figs. 18 and 19 show the successful test for Fuji device ET-102 (450V, 150A device) up to 115A and Fuji ET-127 to 94A without permanent damage. However a Westinghouse (450V, 150A) device was destroyed after four tests at 80A level. Both devices mentioned above were tested in the same tester and the shunt speed for diverting the current is the same. It appears that the energy absorbing capability of a transistor differs from device to device. Some devices can be saved from permanent destruction but some cannot.

4.4 Limitation of Voltage and Current Capability of the Tester

The voltage capability of the tester is limited by the vacuum tube plate voltage rating of the shunt circuit. 1000 Volt is the present limitation of the tester. The current capability of the tester depends critically on how fast the collector current of the DUT can be diverted from the device once the S.B. occurs. To see the details of the action, let's refer to Fig. 22. As can be seen from the figure, about 40 n.S. after the sudden drop of V_{CE} (S. B. occurs), shunt circuit vacuum tube plate voltage collapses and approximately 40 n.S. later, collector current starts to fall and it took approximately 100 n.S. before the current is reduced to zero. It is the time period between the instant S.B. occurs and the instant collector current is reduced to zero that should be shortened as much as possible to increase the tester capability. However, a close look at Fig. 15 reveals that this duration is not as long as the picture indicates. Discussions will be given for three distinct periods of time during the process shunt action.

1. Time period between S.B. occurrence and shunt voltage collapse (40 n.S.),

   This time lapse is required for the S.B. detection signal to travel through the drive circuits for the shunt turn-on. 40 n.S. is as fast as can be practically done, and not much improvement can be expected.

2. Time period between the collapse of plate voltage and the start of current fall (40 n.S.).

   It is found that this time lapse is not real and is caused by the time delay of the measuring current probe/amplifier. In other words, the collector current waveforms shown in all of the figures in this report are all affected by current probe/amplifier delay. The corrected current waveforms should be of the same wave shape but shifted about 40 n.S. to the left.

Consequently, there is little room for improvement for reducing this time period.

3. Time duration for collector current to fall to zero (100 n.S. for 50A).

   This period is determined by the parasitic inductance of the current loop, the supply voltage, and the forward recovery speed of the diode. Parasitic inductance of the current loop is limited by tester package consideration. Fast turn-on diodes (TRW DSR 5600x) have been implemented in the tester. As far as we know, this is the fastest diode meeting the voltage and current requirements of the tester.

The conclusion results from this investigation is that the present tester has reached its physical limitation. Parasitic inductance of the shunt circuit has been reduced as much as physically possible and a very fast diode has also been used.

V. CONCLUSION

A nondestructive reverse-bias second breakdown tester for high power bipolar transistors has been built and tested. The results show that nondestructive testing is successful for current level below 60A. All the devices tested have survived second breakdown many times without noticeable damage. For higher current test, however, device may or may not survive the test depending on individual device characteristics. For some devices, the tester has successfully saved the device from damage up to 115 A level. For other devices, the tester is incapable of saving the device from damage when collector current is above 60 A. It is believed that the energy absorbing capability of a device plays a part in determining whether a nondestructive test can be accomplished at such a high current level.

The speed of the tester shunt circuit is the key to a successful nondestructive tester. To achieve such goal, great attention were paid to the selection of parts and the physical layout of the tester. It's the authors' belief that the shunt circuit has been constructed as compact as practically possible and all the electronics parts used are as fast devices as that available. It is expected that no further improvement can be accomplished without major change of basic design philosophy.

Even with a limited current capability, this tester is still the most powerful nondestructive transistor reverse biased second breakdown tester ever reported. This tester can also be used to test other gate control power semiconductor switches such as Gate Turn-Off Thyristors (GTO's) and Power MOSFETs. With a nondestructive testing capability, device safe operating area can be defined under various driving conditions, and parametric study of a device is made possible.

Vacuum tubes were used in the shunt circuit for the reason that it is the fastest device with voltage rating at or above 1000V. Because of the number of tubes required to handle the desired current level, the shunt circuit is inevitably bulky which increases the parasitic inductance and slows down the shunt action. With the advent of voltage power MOSFET devices or Insulated gate transistor, it is possible that these devices be considered for replacement of tubes to reduce the overall physical size of the shunt circuit and to extend the tester capability beyond 120A and 1000V.

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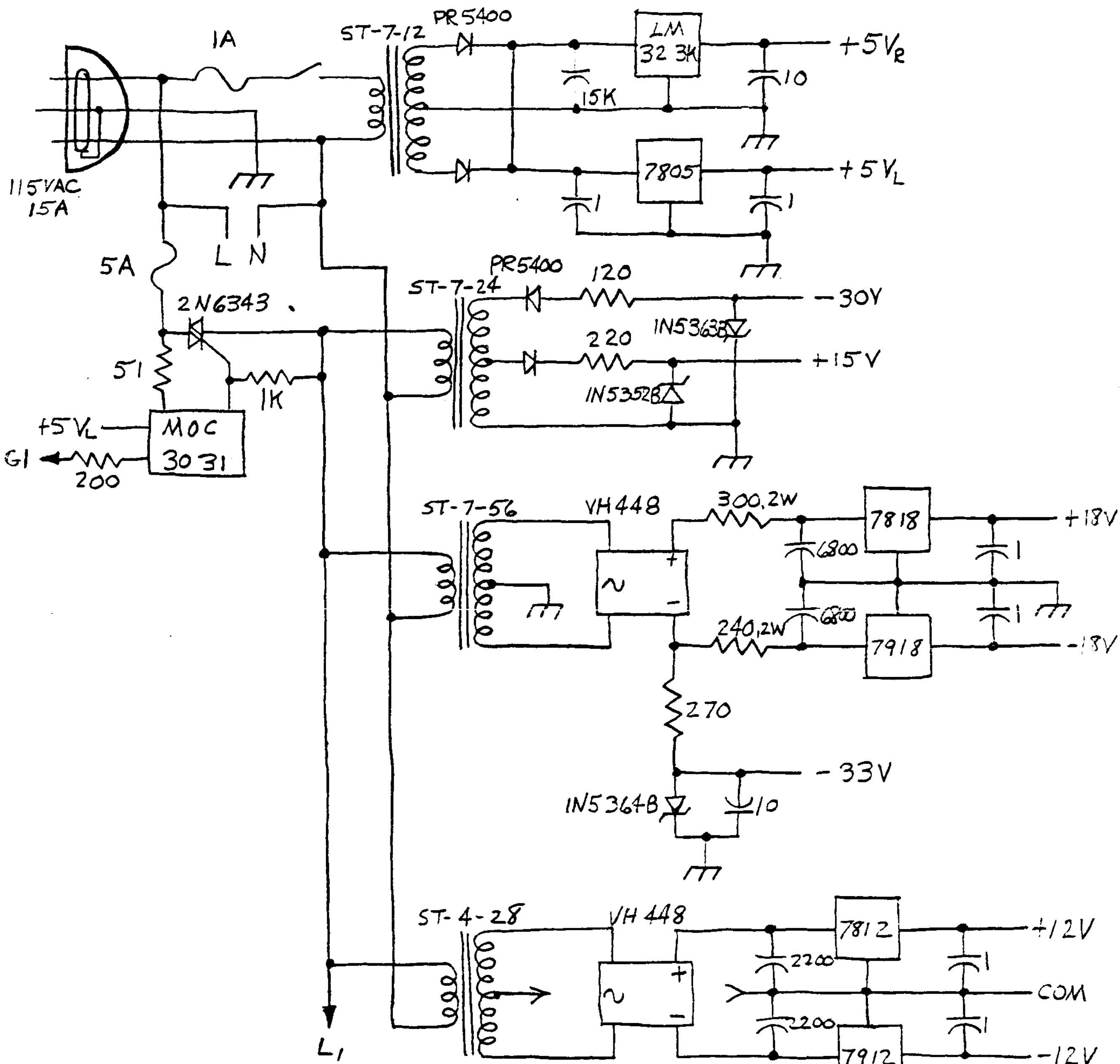
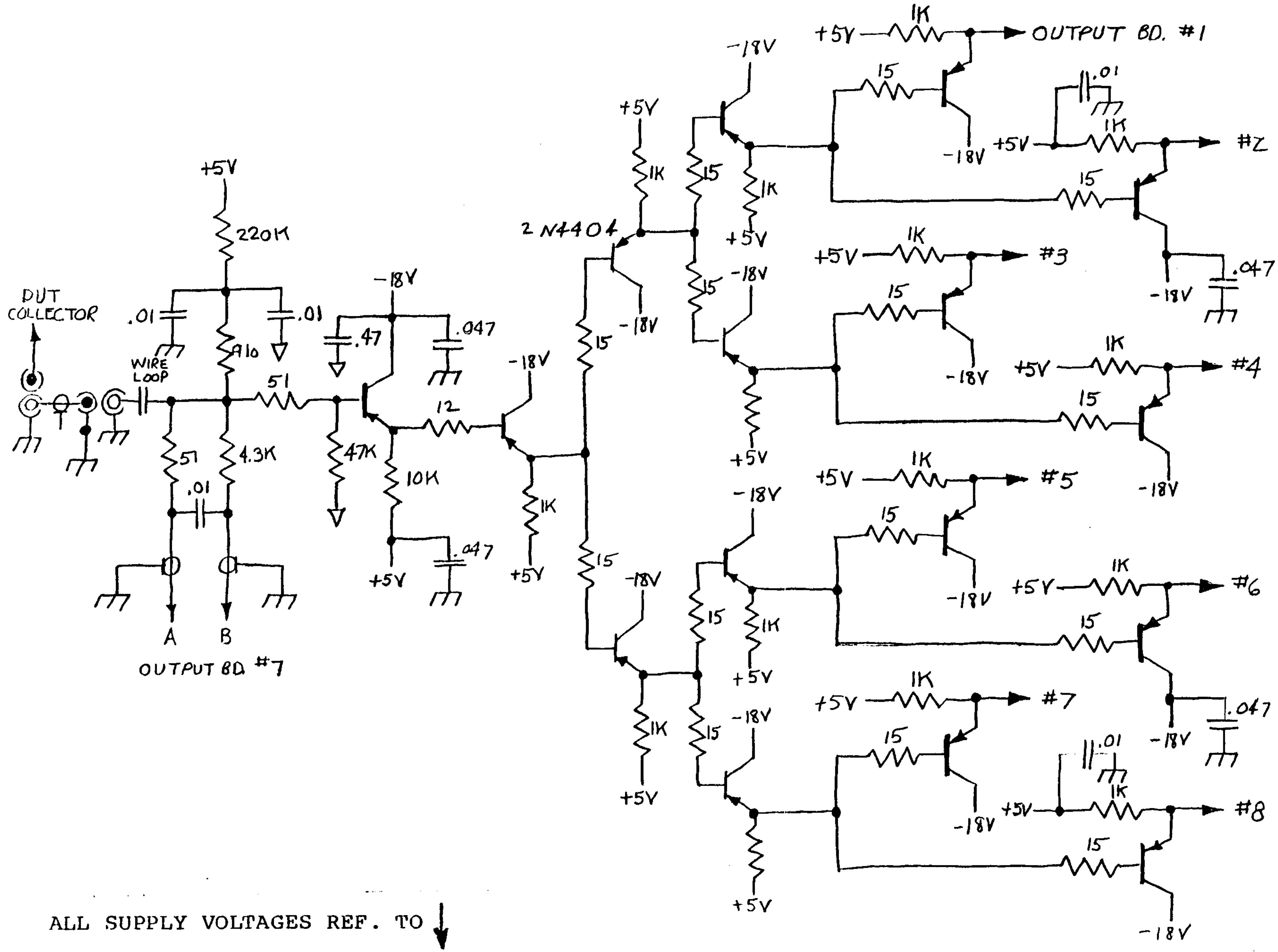
APPENDIX

TESTER CIRCUIT DIAGRAMS

- Base Drive & Logic Board Supplies
- Shunt Input Board
- Shunt Output Board
- Shunt Tube Filament Power Supply
- Shunt & Clamp Power Supplies
- Systems Power-up Sequencer
- Shunt Latching Circuit
- Clamp Supply Filters & Blocking Diodes

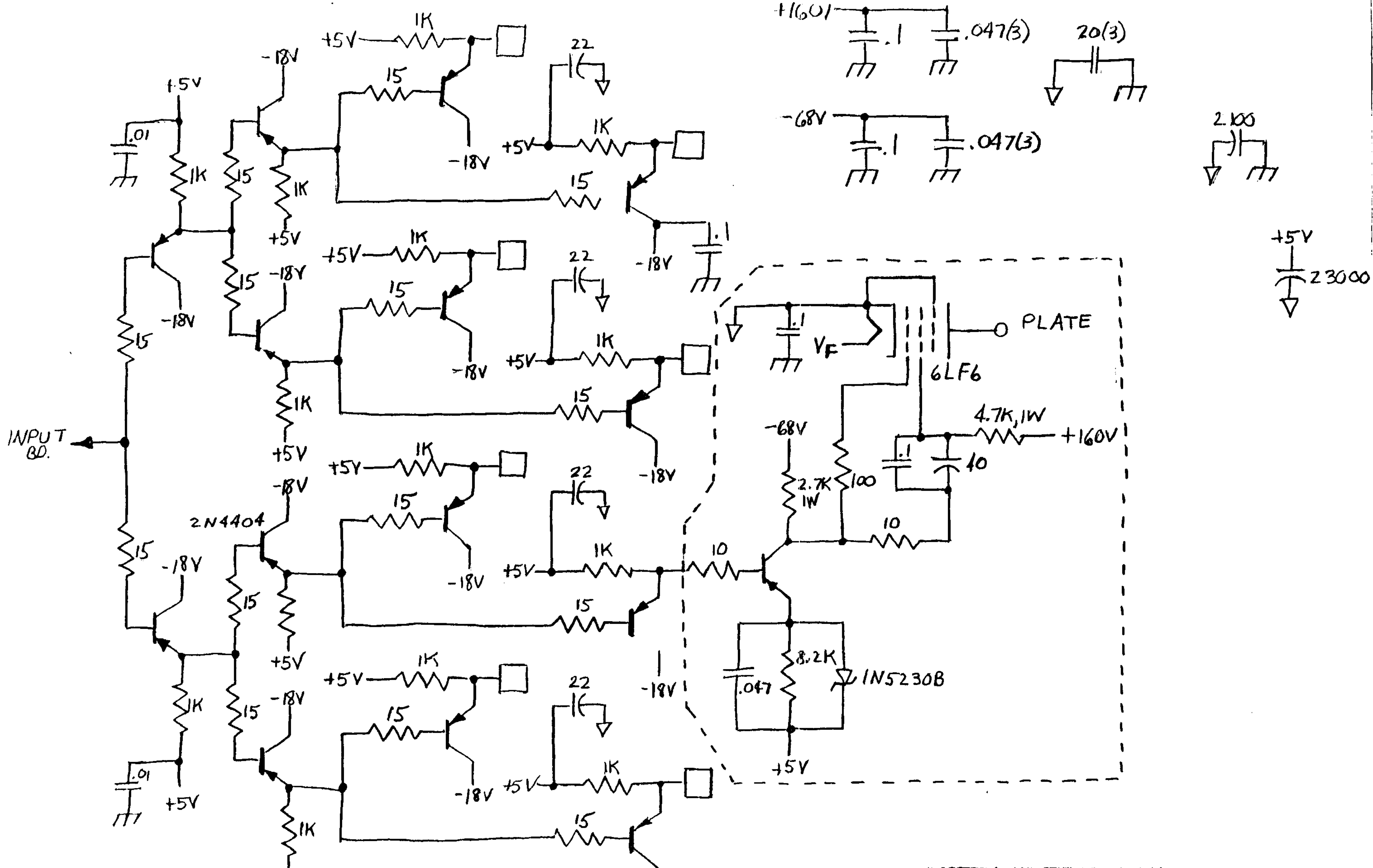


BASE DRIVE & LOGIC POWER SUPPLIES



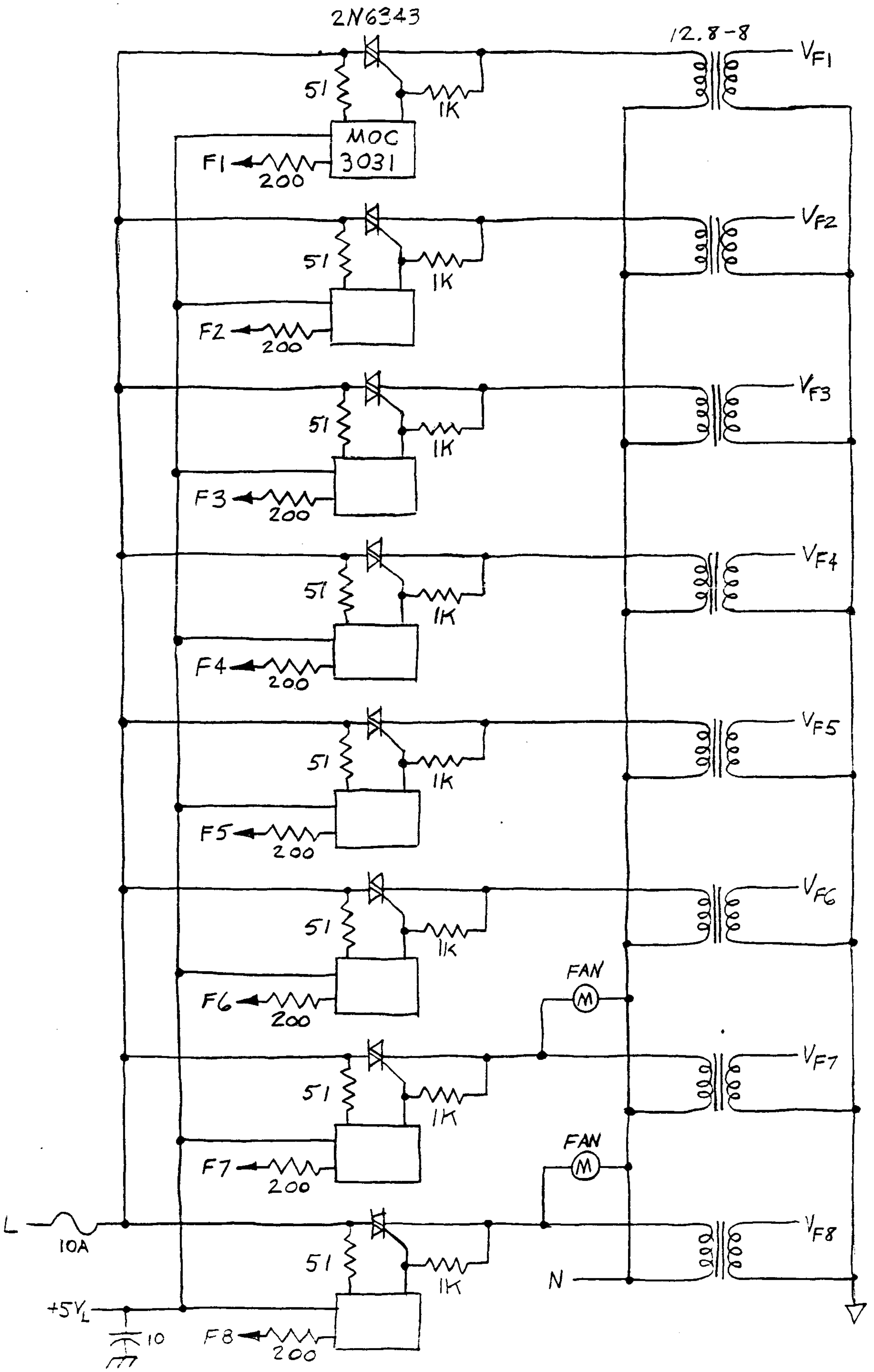
ALL SUPPLY VOLTAGES REF. TO ⏚

SHUNT INPUT BOARD

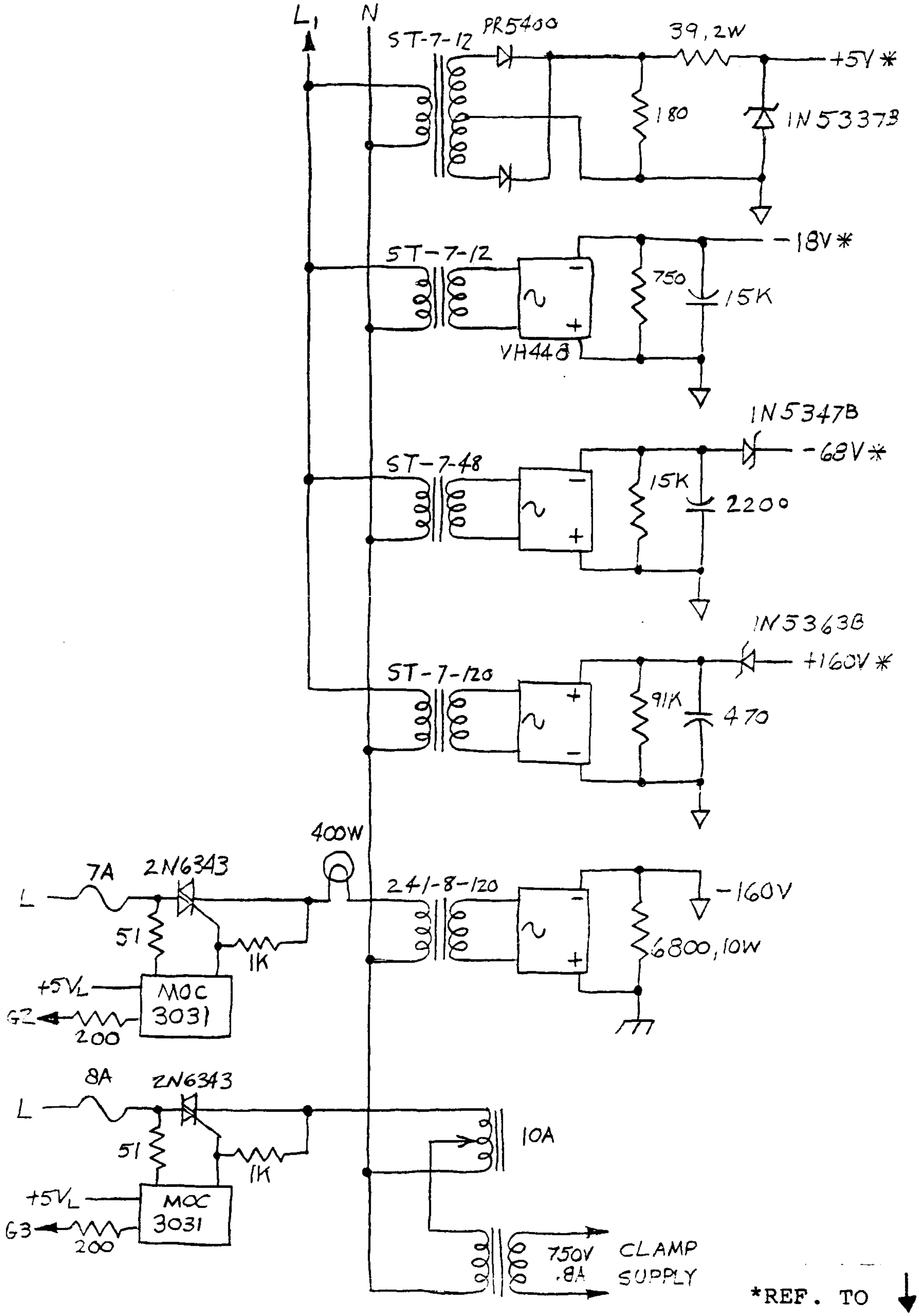


ALL SUPPLY VOLTAGES REF TO

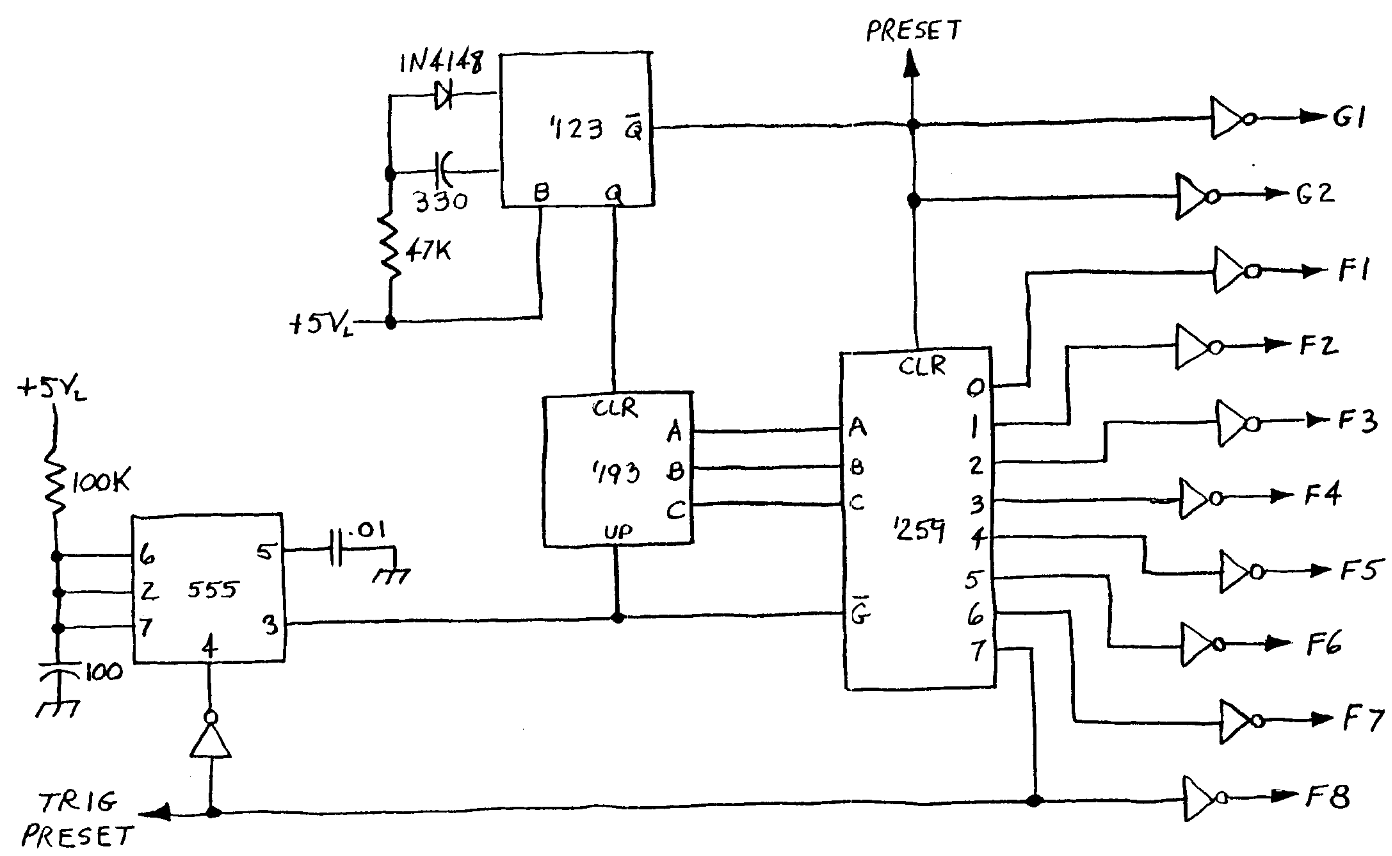
SHUNT OUTPUT BOARD



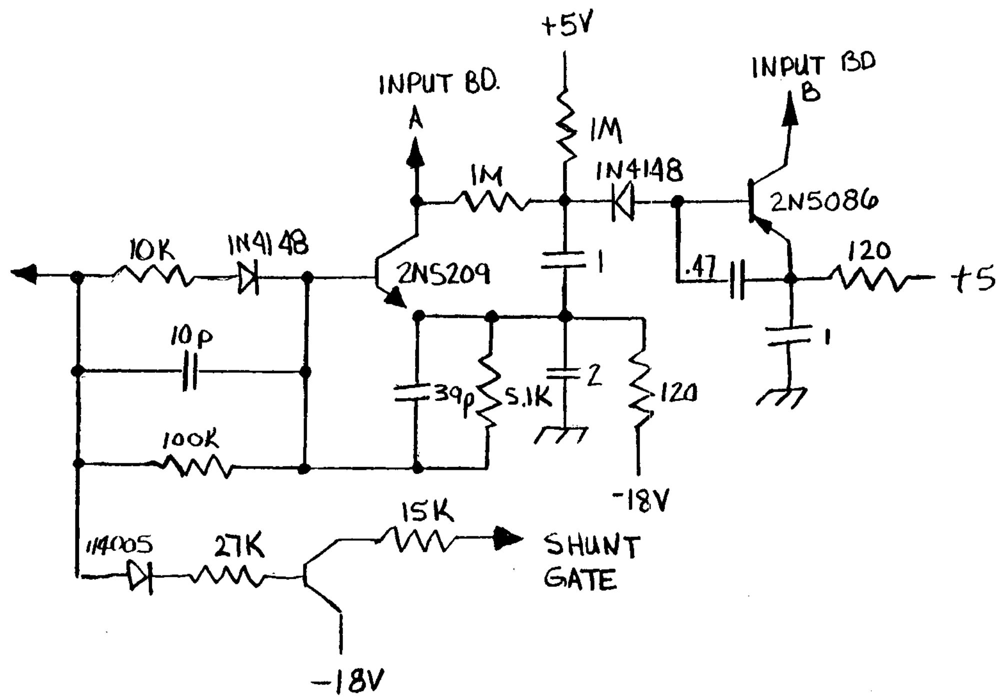
SHUNT TUBE FILAMENT POWER SUPPLY



SHUNT & CLAMP POWER SUPPLIES

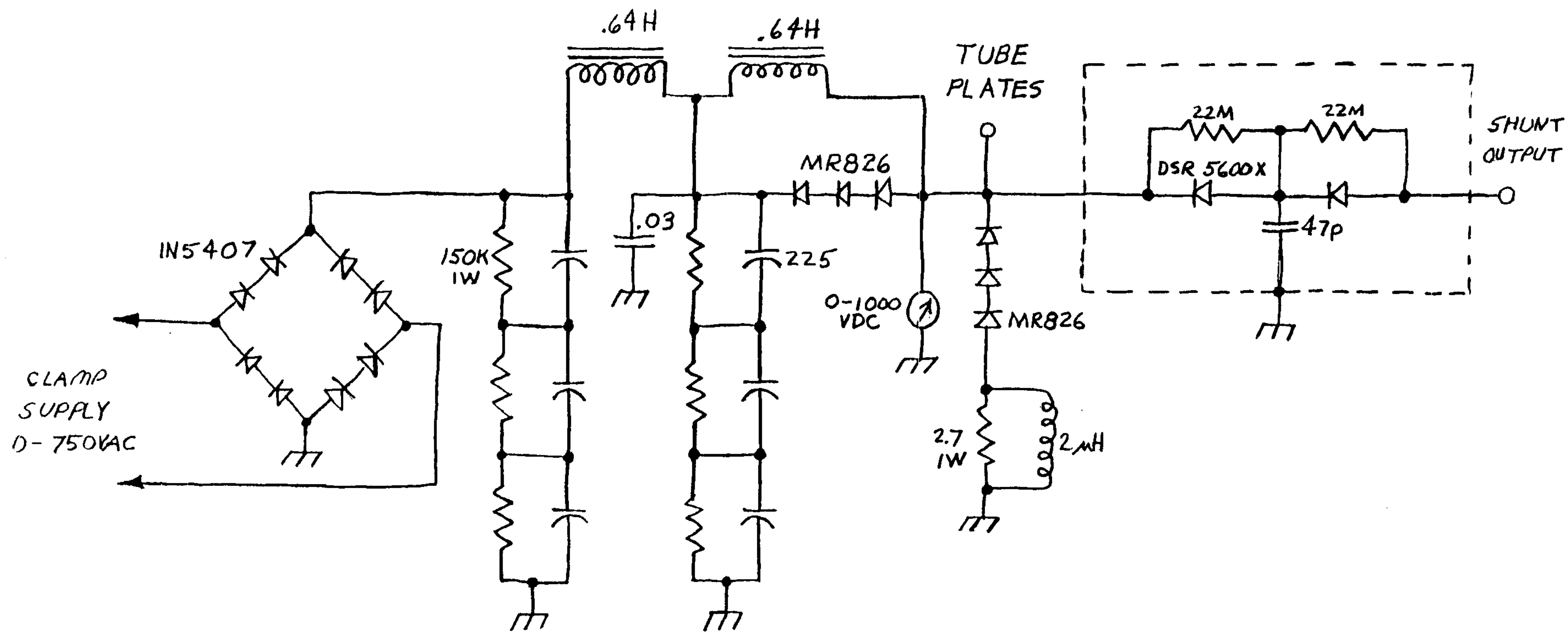


SYSTEMS POWER-UP SEQUENCER



ALL SUPPLY VOLTAGE REF. TO

SHUNT LATCHING CIRCUIT



CLAMP SUPPLY FILTERS & BLOCKING DIODES